

Planetary nebula progenitors that swallow binary systems

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ABSTRACT

I propose that some irregular ‘messy’ planetary nebulae owe their morphologies to triple-stellar evolution where tight binary systems evolve inside and/or on the outskirts the envelope of asymptotic giant branch (AGB) stars. In some cases the tight binary system can survive, in other it is destroyed. The tight binary system might breakup with one star leaving the system. In an alternative evolution, one of the stars of the broken-up tight binary system falls toward the AGB envelope with low specific angular momentum, and drowns in the envelope. In a different type of destruction process the drag inside the AGB envelope causes the tight binary system to merge. This releases gravitational energy within the AGB envelope, leading to a very asymmetrical envelope ejection, with an irregular and ‘messy’ planetary nebula as a descendant. The evolution of the triple-stellar system can be in a full common envelope evolution (CEE) or in a grazing envelope evolution (GEE). Both before and after destruction (if take place) the system might launch pairs of opposite jets. One pronounced signature of triple-stellar evolution might be a large departure from axisymmetrical morphology of the descendant planetary nebula. I estimate that about one in eight non-spherical PNe is shaped by one of these triple-stellar evolutionary routes.

Subject headings: binaries: close – planetary nebulae

1. INTRODUCTION

Planetary nebulae (PNe) are believed by many to acquire their non-spherical morphologies through the interaction of their progenitor with stellar or sub-stellar companions (e.g, see summary by De Marco & Soker 2011). Single stars cannot account for many of the observed properties of elliptical and bipolar PNe (Soker 1998), and single stars cannot maintain a fast rotation over the evolution along the AGB (e.g., Soker & Harpaz 1992; Nordhaus & Blackman 2006; García-Segura et al. 2014). Following earlier studies, (e.g., Bond & Livio 1990; Bond 2000),

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the binary shaping paradigm has gain a critical support in recent years (see reviews by Zijlstra 2015 and De Marco 2015), in particular due to observations of many close binary systems of elliptical and bipolar PNe and a careful analysis of their morphologies, e.g., Akras et al. (2015), Aller et al. (2015a,b), Boffin (2015), Corradi et al. (2015), De Marco et al. (2015), Douchin et al. (2015), Fang et al. (2015), Hillwig et al. (2015), Jones (2015), Jones et al. (2015), Manick et al. (2015), Martínez González et al. (2015), Miszalski et al. (2015), Močnik et al. (2015), Montez et al. (2015), limiting the list to papers from 2015. These close binary systems went through a common envelope evolution (CEE). Some other non-spherical nebulae around AGB and post-AGB stars might have been shaped by wider binary companions that did not go through a CEE (e.g., Lagadec et al. 2011; Bujarrabal et al. 2013; Van Winckel et al. 2014; Decin et al. 2015).

Despite much progress (e.g., Ivanova et al. 2013), the CEE of these systems is not well understood. Numerical simulations cannot eject the envelope in a consistent and persistent manner. Instead, a circumbinary flattened envelope is typically formed, the envelope is not entirely ejected, and spiraling-in ceases too early (e.g., Sandquist et al. 1998; Lombardi et al. 2006; De Marco et al. 2011; Passy et al. 2011, 2012; Ricker & Taam 2012). In light of these difficulties (e.g., Soker 2013) it has been suggested that in many cases jets launched by the more compact companion, including main sequence secondary stars, facilitate envelope ejection in a CEE (e.g., Soker 2013, 2014).

If the jets launched by the secondary star remove the entire envelope outside the secondary orbit as it spirals in, the formation of a CE is prevented. Instead, a grazing envelope evolution (GEE) takes place, where the binary system might be considered to evolve in a state of just entering a CE phase (Soker 2015). The companion grazes the envelope of the giant star, and both the orbital separation and the giant radius shrink simultaneously. Tidal interaction that leads to orbit shrinkage makes the GEE an alternative to the CEE in cases where jets efficiently remove the envelope. When the companion is massive enough to bring the giant envelope to synchronization, the orbit during the GEE does not shrink much, and might even increase. Gorlova et al. (2012) found that the companion to the post-AGB star BD+46°442 launches jets. The orbital period of this binary system is 140.77 days. Gorlova et al. (2015) reported the detection of a collimated outflow from the companion of IRAS 19135+3937, a post-AGB binary system with an orbital period of 127 days. Both these systems are highly compatible with the expectation from the GEE when the companion manages to maintain the AGB star in synchronization with the orbital period. I suggest that these systems evolved indeed through a synchronized GEE.

The multitude of processes that are involved in the CEE and GEE phases, such as mass loss through the L_2 Lagrangian point and jets launching with or without precession, and the large parameter space of binary system properties, ensure that each PN is ‘unique’ in its morphology (Soker 2002). As well, the multitude of processes place PNe on the crossroad of many astrophysical objects, e.g., novae, symbiotic binaries, and massive binary systems such as η Carinae, and of

many generic astrophysical evolutionary phases, e.g., CEE, jet-inflated bubbles, and stellar merger (De Marco 2015). PNe are directly connected also to type Ia supernovae (Tsebrenko & Soker 2015) and to intermediate luminosity optical transients (ILOTs; Soker & Kashi 2012). These processes and objects involve strongly interacting binary systems.

On top of the large parameter space of binary system properties, a tertiary star can be added. In previous papers mainly wide tertiary stars were mentioned. Namely, the secondary and tertiary stars orbit the AGB progenitor of the PN, and not each other. A wide stellar companion, to a central single star or a central binary system, at orbital separations of $a_3 \approx 10 - \text{several} \times 10^3$ AU can cause the PN to possess departure from axisymmetry and to have an equatorial spiral pattern (Soker 1994). Soker et al. (1992) proposed that the departure of the PN NGC 3242 from axisymmetry was caused by a tertiary star of a mass of $M_3 \approx 1M_\odot$ at an orbital separation of $a_3 \approx 4000$ AU. In addition, a very wide tertiary star, $a_3 \gtrsim 10^3$ AU might form a small bubble inside the nebula (Soker 1996).

Engulfed binary systems were discussed in the past as well. Exter et al. (2010) proposed that the AGB stellar progenitor of the PN SuWt 2 engulfed a tight binary system of A stars. They (see also Bond et al. 2002) proposed that PNe with a high density ring in the equatorial plane can result from triple-stellar evolution. In that scenario the tight binary is engulfed by the primary star, and survives most or all of the CEE. It might merge later on as the stars of the binary system evolve (Bond et al. 2002).

In the present paper I add more to this rich variety of binary and triple evolutionary tracks by considering new evolutionary routes where instead of a single secondary star, a tight binary system is swallowed by the AGB or red giant branch (RGB) star. The typical initial orbital period of the tight binary system is $P_{\text{ZAMS},23} \approx \text{day} - \text{month}$, while the orbital period of the triple system (the tight binary and the primary star around their mutual center of mass) is $P_{\text{ZAMS},123} \approx 1 - 10$ yr. Such systems are known to exist (e.g., Tokovinin et al. 2006). This preliminary study sets down the foundations for further studies, including three-dimensional hydrodynamical simulations of triple-CEE and triple-GEE. In section 2 I describe the triple-stellar systems that are considered here. In section 3 I describe the different possible fates of such triple systems, and the general departure from symmetry of the descendant PNe. I summarize in section 4.

2. SETTING THE PROBLEM

2.1. Expectation

Let us estimate the fraction of AGB stellar progenitors of PNe that interact with a tight binary system, rather than with a single secondary star. Consider main sequence stars that are expected to

evolve along the upper AGB, hence having a zero age main sequence (ZAMS) mass of $M_{\text{ZAMS},1} \simeq 1 - 8M_{\odot}$. Consider only those primary stars that have a main sequence stellar companion with a mass of $M_2 < M_{\text{ZAMS},1}$, with an initial semi-major axis $a_{\text{ZAMS},123}$. The question is the following. What fraction of these systems have a tertiary star with a mass of $M_3 < M_2$ that orbit the secondary star in a tight orbit, $a_{\text{ZAMS},23} < a_{\text{ZAMS},123}$? I call this fraction $\eta_{1,23}$.

In their review article Duchêne & Kraus (2013) give for stars with ZAMS mass in the range $M_{\text{ZAMS},1} = 1.5 - 5M_{\odot}$ a multiplicity frequency of MF > 50% and a companion frequency of CF = $100 \pm 10\%$ (their Table 1 and figure 1). For solar type stars the fraction of systems with $n \leq 6$ stars goes approximately as $N(n) \approx k2.5^{-n}$, and $\approx 25\%$ of systems of solar type stars have $n \geq 3$ (Duchêne & Kraus 2013, section 3.1.5). For the mass range $1.5 - 5M_{\odot}$ that is more relevant for Galactic PNe, I take the fraction of systems with n stars to go as $N(n) = kx^{-n}$ as well. I limit the systems for up to 6 stars. I find that to account for a MF > 50% and a companion frequency of CF = 100 the value is $x \approx 1.9$ (taking $x = 2$ that gives CF = 90 does not change the results much). The fractions of systems with n stars, $N(n) \propto 1.9^{-n}$, are as follows. Single star systems $N(1) = 0.49$, binary systems $N(2) = 0.25$, triple systems, $N(3) = 0.13$, and then $N(4) = 0.07$, $N(5) = 0.04$, and $N(6) = 0.02$. These values give MF = 51% and CF = 98%.

Let us first consider only binary and triple systems. In the triple-stellar systems the tertiary star can orbit the secondary star, the primary star, or both. We now consider the first possibility which can lead to a case where an AGB star swallows a tight binary system of two main sequence stars. I crudely assume that in about third of all triple-stellar systems the initial more massive star is at a larger orbital separation from the two lighter ones. This is a fraction of $\simeq N(3)/3 = 0.043$ of all systems. The rest, ≈ 0.09 of all systems, are triple-stellar systems that are not the triple systems consider now. The fraction of the systems considered now to all cases with binary interaction under these assumptions is

$$\eta_{1,23} = \frac{\text{tight } (M_2, M_3) \text{ sytems}}{\text{all multiple systems}} \approx \frac{N(3)/3}{N(2) + N(3)} \approx \frac{0.043}{0.25 + 0.13} = 0.11. \quad (1)$$

Three considerations increase the fraction of PNe shaped by triple-stellar systems relative to the value of $\eta_{1,23}$ given by equation (1). Firstly, when the tertiary star and the primary star closely orbit each other, the tertiary might prevent the primary from formation a PN by causing a too early envelope removal. This reduce the denominator in equation (1). Secondly, when the higher multiple systems are considered the probability of the AGB primary star to interact with a binary system rather than with a single secondary star increases. If for example, third of the quadruple, quintuplet, and sextuplet stellar systems are taken to be relevant to the present study, then

$$\eta_{1,23} \approx \frac{[N(3) + N(4) + N(5) + N(6)]/3}{N(2) + N(3) + N(4) + N(5) + N(6)} \approx \frac{0.26/3}{0.51} = 0.17. \quad (2)$$

Thirdly, in some systems one of the stars of the tight binary system might be a WD. This is the case when the initially most massive star is in a tight orbit, and it forms a WD without destroying the tight binary system. The initially second most massive star is in a larger orbital separation from the tight binary system. When it evolves on the upper AGB it might swallow the tight binary system, now composed of a WD and a main sequence star.

Two considerations reduce the fraction of PNe shaped by triple-stellar systems relative to the value of $\eta_{1,23}$ given by equations (1) and (2). Firstly, some PNe can result from solar-like stars. These have lower multiplicity frequency and companion frequency than stars with initial mass in the range $1.5 - 5M_{\odot}$ (Duchêne & Kraus 2013). Secondly, some PNe might be shaped by planets. I assume here that single star do not form bright PNe. But planets might shape PNe as well, adding to non-spherical PNe, hence increasing the denominator in equations (1) and (2). On the other hand, one then needs to consider AGB stars that swallow planetary systems. Namely, instead of a tight binary system, the AGB swallows a tight planetary system. Such systems can also shape PNe simpler to triple-stellar systems if the planet is massive enough.

Taking these considerations and the large uncertainties I estimate that about one in ten to one in six ($\approx 10\% - 17\%$) of PN progenitors that evolved through a binary interaction, actually went through an interaction with a tight binary system. Crudely, about one in eight PNe shaped by binary systems was actually shaped by a tertiary system.

In this work I consider mainly cases where the tight binary system does not survive the CEE. It is not crucial for the general results, but it is my expectation that in most, but not all, cases of CEE only two stars survive as a bound binary system. One of the two stars in the tight binary system, mostly the tertiary star, is expected to merge either with the secondary star or the primary core, or be ejected from the system. In a minority of cases all three stars are expected to survive. This hypothesis that most tight binary systems do not survive, should be examined by detail numerical simulations.

One case where the tight binary system seems to have survived the CEE is the PN SuWt 2 (Exter et al. 2010). A possible example for evolution where the tight binary system did not survived the CEE, but all stars survived and stayed bound is the triple pulsar system PSR J0337+1715. The pulsar is orbited by two low mass white dwarfs having periods of 1.63 day and 327 day (Ransom et al. 2014). Sabach & Soker (2015) proposed the following scenario for this system (for an alternative scenario see Tauris & van den Heuvel 2014). A tight binary system of two main sequence stars was tidally and frictionally destroyed inside the envelope of a massive star that formed a PN. Only later in the evolution the central massive ONeMg white dwarf experienced an accretion-induced collapse and formed the neutron star. That scenario includes a new ingredient of a binary system that breaks up inside a CE. As well, the scenario employs an efficient envelope removal by jets launched by the main sequence stars immersed in the giant envelope, and the GEE.

2.2. Energy considerations

Two types of energy can be associated with the tight binary system. The first is the energy that is need to breakup the tight binary system, the breakup energy

$$E_{b,23} = \frac{1}{2} \frac{GM_2M_3}{a_{\text{ZAMS},23}}. \quad (3)$$

The second one is the energy the binary system releases if it merges, the merger energy

$$E_{m,23} \approx \frac{1}{2} \frac{GM_2M_3}{R_2}, \quad (4)$$

where R_2 is the radius of the secondary star. The amount of energy released depends on the response of the secondary star to the accretion of the tertiary star, so the value given above is an estimate.

More constructive is to define dimensionless quantities. Let $a_{f,\text{CE}}$ be the final orbital separation of the secondary star from the core of the primary star according to the energy prescription of the CEE (e.g., Webbink 1984; Tauris & Dewi 2001; Ivanova et al. 2013) that states

$$E_{\text{env}} = \frac{1}{2} \alpha_{\text{CE}} \frac{GM_{\text{core}}M_2}{a_{f,\text{CE}}}, \quad (5)$$

where E_{env} is the binding energy of the giant envelope, α_{CE} is the CE- α parameter, and M_{core} is the mass of the giant core. The two dimensionless ratios are

$$\xi_b \equiv \frac{E_{b,23}}{E_{\text{env}}} \approx 0.5 \left(\frac{M_3}{0.5M_{\text{core}}} \right) \left(\frac{2a_{f,\text{CE}}}{a_{\text{ZAMS},23}} \right) \left(\frac{\alpha_{\text{CE}}}{0.5} \right)^{-1}, \quad (6)$$

and

$$\xi_m \equiv \frac{E_{m,23}}{E_{\text{env}}} \approx 5 \left(\frac{M_3}{0.5M_{\text{core}}} \right) \left(\frac{a_{f,\text{CE}}}{5R_2} \right) \left(\frac{\alpha_{\text{CE}}}{0.5} \right)^{-1}. \quad (7)$$

Typical values of $M_{\text{core}} \simeq 0.6M_{\odot}$, $a_{f,\text{CE}} \approx 2.5R_{\odot}$ (final core-secondary orbital period of about half a day), $R_2 = 0.5R_{\odot}$ ($M_2 \approx 0.5M_{\odot}$), $a_{\text{ZAMS},23} \approx 5R_{\odot}$, and $M_3 \approx 0.1 - 0.5M_{\odot}$ were used for the above scaling.

Equation 6 shows that the breakup of the tight binary requires a non-negligible amount of energy. This comes on the expense of the kinetic energy of the secondary or the tertiary star; one star of the tight binary moves to larger orbit, or even escape the system, and the other star dives further in.

Equation 7 shows that a merger of the tight binary system can in principle eject a large fraction of the giant envelope, and at high speeds. The merger occurs on several times the dynamical time

of the tight-binary system, which is much shorter than the orbital period of the triple-system. This implies a very asymmetrical mass ejection to one side. If the two orbital planes, of the tight binary system and of the triple system, are parallel, the ejection process maintains the mirror symmetry about the orbital plane. But if the two planes are inclined to each other, no axis or plane of symmetry are expected in the mass ejection due to the tight-binary merger. A ‘messy’ expanding shell is expected to be formed.

Since most PN central stars have masses in the range $M_{\text{core}} \approx 0.6 - 1 M_{\odot}$, equations 6 and 7 with the initial constraints $M_3 < M_2 < M_{\text{ZAMS},1}$ show that on average the role of the tight-binary system is expected to increase with primary mass, as the mass of M_3 can be larger. In the case of the tight-binary merger process even a tertiary of $M_3 \approx 0.05 - 0.1 M_{\text{core}}$ can play a significant role. This includes a brown dwarf tertiary.

The energy of the merger can be carried by jets, or a wide outflow, launched by the accretion disk or belt formed around the secondary star from the destroyed tertiary star. Another source of energy, that can exist also in the case of a single secondary star (namely, a binary system), is the accretion of giant stellar envelope mass onto the secondary (or tertiary) star. The accretion disk or belt can launch jets that facilitate the removal of the giant envelope. The energy carried by the jets can be expressed as (Soker 2014)

$$\xi_{\text{jets}} \equiv \frac{E_{\text{jets}}}{E_{\text{env}}} \approx \frac{M_{\text{acc}}}{M_{\text{core}}} \frac{a_{\text{f,CE}}}{R_2} \frac{1}{\alpha_{\text{CE}}} = 1 \left(\frac{M_{\text{acc}}}{0.1 M_{\text{core}}} \right) \left(\frac{a_{\text{f,CE}}}{5 R_2} \right) \left(\frac{\alpha_{\text{CE}}}{0.5} \right)^{-1}, \quad (8)$$

where M_{acc} is the mass accreted by the secondary (or tertiary) star.

3. OUTCOMES

3.1. Tight binary in a wide orbit

3.1.1. Evolution

The first scenario for a giant star orbited by a tight binary system evolves no CEE or GEE of a giant with a tight binary system, but rather accretion by the tight binary system from the dense wind of the evolved giant star. It was studied in the past (Soker 2004 where more details can be found), and it is updated here, as the PNe listed then might not be compatible with new expectations.

In that study it was found that when the orbital plane of the accreting tight binary system and the orbital plane of the triple system (the plane of the tight binary and the giant star) are not parallel to each other, the accreted mass onto one or two of the tight binary system components has high specific angular momentum. For a large fraction of triple-stellar systems accretion disks are

expected to form around one or two of the tight binary stars, and launch jets. The axis of jets will be almost parallel to the orbital plane of the triple-stellar system. One jet is blown outward relative to the wind, while the other jet passes near the mass-losing star, and is more likely to be deflected and slowed down by the giant wind. This flow of asymmetrical jets breaks the mirror symmetry of the descendant PN. Namely, the two lobes or two opposite blobs on the two sides of the equatorial plane will not be equal. The long-period orbital motion will lead to a departure from axisymmetry, i.e., there is no symmetry around the angular momentum axis (the orbital motion itself does not break the mirror symmetry about the equatorial plane).

At the end of the AGB phase when the mass-loss rate is very high, an accretion disk might form in tight binary systems up to $\approx 400 - 800$ AU from the giant star. This leaves a space for a fourth star to orbit the AGB star at a close orbit of few AU. The closer stellar companion to the AGB star strongly interacts with the AGB star and leads to the formation of an elliptical or a bipolar PN. Again, the AGB star itself engulfs only one star, if at all. As we see next, it seems that the fourth star is required to form a PN.

3.1.2. *The descendant PNe*

All three stars survive. The triple-system orbit increases due to the mass lost from the AGB stars. It can be by a factor of $\approx 2 - 3$, depending on the initial and final masses. The orbit of the tight binary system decreases by a small amount as a result of mass accretion.

The following PNe were listed in 2004 (Soker 2004) as possessing morphologies compatible with the expectation from a far-away tight binary system that accretes mass from the wind and launches jets.

He 3-1357 (PN G331.3-12.1). This PN has a dense ring and small lobes protrude from the nebula (Bobrowsky et al. 1998). However, no single axis of symmetry, nor a point-symmetry, and nor a plane of symmetry, can be defined for this nebula.

PN NGC 6210 (PN G043.1+37.7). This PN, as another example of a PN that was proposed to have been shaped by a triple-stellar system (Soker 2004), is a ‘messy’ PN, with a general elliptical structure with unequal sides, blobs, filaments and two pairs of opposite jets protruding from the main ‘messy’ (irregular) shell (e.g., Balick 1987; Pottasch et al. 2009; I will return to this PN below).

IC 2149 (PN G166.1+10.4) (Vázquez et al. 2002); **M1-59 (PN G023.9-02.3)** (Manchado et al. 1996; Sahai et al. 2011); **NGC 1514 (PN G165.5-15.2)** (Hajian et al. 1997; Muthu & Anandarao 2003); **NGC 6886 (PN G 060.1-07.7)** (Sahai et al. 2011). These four PNe were also in that list of PNe shaped by triple or quadruple star systems.

However, in the years since 2004 a picture has emerged that for a bright PN to be formed the mass loss from the AGB star must be enhanced by a strong binary interaction (De Marco et al. 2004; Soker & Subag 2005; Moe & De Marco 2006). As such, it is less likely that the above listed PNe are compatible with a far-away triple system alone. They might be more compatible with the engulfment of a tight binary system (as suggested below for NGC 6210). We therefore need to consider one of two scenarios.

In the first scenario the tight binary system is close to the AGB star, and accretes mass from the AGB envelope via a Roche lobe overflow rather than from a wind. The binary system is massive enough to maintain the triple system in synchronization and against the Darwin instability, and the triple-stellar system survives the entire evolution with no CEE or GEE phases. The outcome is a point symmetric bipolar PNe with a triple star system inside: a tight binary system orbiting the remnant of the AGB core at ≈ 1 AU. In the case that the two orbital planes are parallel, the morphology of the descendant PN will be more or less as expected in binary evolution, but possibly with a wide and pronounced jets' precession. When the two orbital planes are inclined to each other, a point-symmetric PN with complicated structure that is hard to predict will emerge.

In the second scenario there is a quadruple-stellar system. The fourth star is closer to the AGB star than the far-away tight binary system. For the tight binary system to make a mark on the descendant PN, it should be closer than ≈ 100 AU. I expect the tight binary system to add an opposite pair of bullets or two jet-inflated small bubbles. As well, the motion around the center of mass of the quadruple systems leads to departure from axisymmetry. Since we are now considering quadruple systems, such PNe are very rare. It is hard to define the exact characteristics of the descendant PNe, and more so to find one. Let me give one example that might be compatible with a quadruple system with a wide tight binary system

NGC 6578 (PN G010.8-01.8) (Palen et al. 2002; Sahai et al. 2011). This is an elliptical PN containing parts with not well defined symmetry (Sahai et al. 2011). The PN is presented in Fig. 1. It has two pairs of opposite unequal structures. One pair has a small lobe on each side of the center, but they are unequal in size and shape. Outside there are two opposite bullets, marked with the red line on the figure. The other pair has dense structures, one is an arc and the other is a 'hand fan' of filaments. The two axes are inclined to each other. It is hard to tell at this stage which axes is due to the closer fourth star, and which is from the far-away tight binary system.

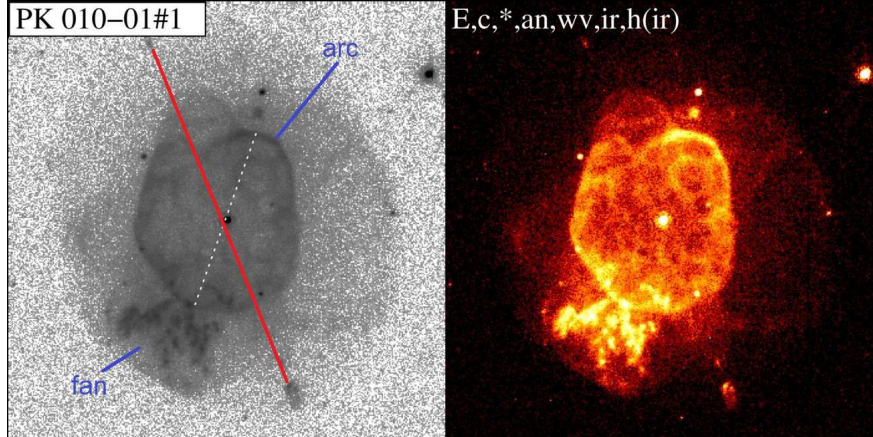


Fig. 1.— An image of NGC 6578 from Sahai et al. (2011). This morphology might be compatible with a tight binary system in a wide orbit. According to the proposed scenario, both the closer fourth star and the far-away tight binary systems, each launched a pair of jets. The two axes of the pairs are inclined to each other. One axis marked by Sahai et al. (2011) in dashed-white, and the other added here as a red solid line.

3.2. Ejecting a star

3.2.1. Evolution

In the interaction of three point masses one possible outcome is that the lowest mass object is ejected from the system, and the two other bodies form a bound binary system. The case where the primary star has an envelope of the size of the orbital orbit and the tight binary system breaks up inside the giant envelope has not been studied numerically. The breakup of the binary system was discussed somewhat speculatively by Sabach & Soker (2015), as summarized in section 2.1 here. Sabach & Soker (2015) were interested in the case when the two orbital planes are parallel to each other. Here we refer to inclined planes as well.

The initial system is composed of a tight binary system with an orbital separation of $a_{\text{ZAMS},23} \approx \text{several} \times 10R_{\odot}$, that orbit a primary star of mass $M_{\text{ZAMS},1} \simeq 2 - 6M_{\odot}$, at a triple system orbital separation of $a_{\text{ZAMS},123} \approx \text{several} \times a_{\text{ZAMS},23} \approx 1 - 5 \text{ AU}$. The range of the primary mass is dictated by the condition that its maximum radius on the RGB will be much smaller than its maximum radius on the AGB when engulfment supposes to take place. The ratio of the two orbital separations ensures dynamical stability (e.g. Mardling & Aarseth 2001) before engulfment occurs, and a marginal stability when engulfment starts after the triple system orbit has decreased.

At the upper AGB the primary star expands. Due to tidal forces the tight binary system spirals-in toward the primary star. Now the ratio of the triple system orbital separation to the tight binary

orbital separation decreases, and the system might become dynamical unstable. If the tight binary system breaks-up before engulfment occurs, one star, most likely the lowest mass one, is ejected from the system, and we enter a regime of binary interaction.

In the case that the tight binary system does not breakup before engulfment, the two stars start to orbit inside the giant envelope. In these systems the orbital separation of the tight binary system is large, of the order of magnitude of the density scale height in the giant envelope. Hence, initially only the star closer to the primary is inside the envelope. This star might accrete mass, forms an accretion disk, and launches two opposite jets. At the same time the other star is tens of R_{\odot} outside the giant photosphere. In the scenario discussed in this subsection, the jets remove the envelope outside the binary system. Namely, the system is in the GEE phase. Each of the two stars in the tight binary system spends only part of the orbit inside the giant envelope. The jets are expected to exist during part of the orbital period of the tight binary system, only when the accreting star(s) is(are) inside the envelope.

Only the star inside the envelope suffers a strong gravitational drag. The other star feels strong tidal forces. This situation changes after about a half orbital period, and so on. This differential gravitational drag on the two stars and the tidal forces acting on the star that is outside the envelope, might change the outcome in two ways, as speculated by Sabach & Soker (2015). Firstly, instead of being ejected from the system, the star that was supposed to escape might end at a large, but bound and stable, orbit. Secondly, when the masses ratio $q_{32} = M_3/M_2$ is not much below 1, then in some cases the star $M_2 > M_3$ might end up at a larger orbital separation.

The break-up is expected to take place when the binary system is in the outer parts of the AGB star, in a triple system orbital separation of $a_{123} \gtrsim 100R_{\odot}$. After the ejection of one star from the envelope, the two remaining stars of the inner binary system, either the primary with the secondary or the primary with the tertiary, continue in a binary interaction. The inner binary system can continue the GEE, hence the two stars survive, or enter a CEE. As in binary interaction evolution, the CEE can end with a close binary system, or in a merger.

One of the four following types of a bound system can be found at the center of the descendant PN in cases where the tight binary system breaks apart. (1) A single star. This is the case if one of the tight binary stars was ejected and the other merged with the core. (2) A close binary system. This is the case if one of the tight binary stars was ejected and the other survived the CEE or the GEE phase. (3) A wide and eccentric binary system. This is the case if one of the tight binary stars was thrown to a large eccentric orbit, and the other merged with the core. (4) A triple system of a wide and eccentric star, and a much closer binary system. This is the case if one of the tight binary stars was thrown to a large eccentric orbit, and the other survived the CEE or the GEE phase. If the tight binary system survives the CEE, the central system will be of a post-AGB star orbited by a tight binary system (Exter et al. 2010).

3.2.2. *The descendant PNe*

The descendent nebula possesses a structure of two non-spherical structures resulting from two mass loss phases with a relative displacement between them. The two intensive mass loss phases are before and after the breakup of the tight binary system. Before the breakup the mass loss occurs around the center of mass of the triple systems. Jets are formed as the tight binary system accretes from the AGB envelope via a Roche lobe overflow. After the ejection of one of the stars of the tight binary system, the mass loss continues around the center of mass of the remaining binary system. This system moves to the opposite direction of the ejected star. Therefore, the nebular part formed after the breakup has a general velocity relative to the outer nebula. This descendant PN has a displacement from axisymmetry. If the two orbital planes are not parallel to each other, the system will not have even a mirror symmetry about any orbital plane. In cases where the tight binary system survives, only the first of these two phases will take place, and the descendant PNe will be less complicated, although the departure from sphericity can be very large, e.g., having an equatorial ring (Exter et al. 2010).

Let us consider one example out of a very large parameter space. Say at breakup the binary system is at $a_{123} = 1$ AU. The masses are $M_1 = 3M_\odot$, $M_2 = 0.5M_\odot$, and $M_3 = 0.3M_\odot$. Let us take the tertiary star to become unbound and ejected from the system with a terminal velocity of a fraction χ of the escape speed from the system, $v_{ej,3} \approx 40(\chi/0.5)$ km s⁻¹. From momentum conservation the remaining binary system moves with respect to the center of mass at $v_{12} \approx 3(\chi/0.5)$ km s⁻¹. For a nebula expanding at $\approx 10 - 20$ km s⁻¹ this leads to an observable departure from axisymmetry.

The PNe are not expected to be too ‘messy’, but might possess no symmetry axis and no plane of symmetry. Possible structures are like those of the following PNe. (One should be aware that some morphological features can be accounted for also in binary interaction, with no need for triple-stellar evolution.)

IC 2553 (PN G285.4-05.3). It has a point-symmetric structure, but with a displacement of different structures (Corradi et al. 2000). It is possible that a triple-stellar system caused this structure.

M 1-26 (PN G358.9-00.7). On top of the point-symmetric structure this PN possesses departure from axisymmetry along each line that connect two opposite features (Sahai & Trauger 1998). I suggest here that a triple-stellar system shaped this PN. An unbound low mass main sequence star might exist near the center.

M 1-6 (PN G211.2-03.5). This PN has two lobes, and a smaller and denser inner region (Sahai et al. 2011; Otsuka et al. 2014). Its image is presented in Fig. 2 taken from Sahai et al. (2011). This PN has neither axisymmetry nor mirror symmetry. Its structure is compatible with the expectation of a triple-stellar system shaping discussed in this subsection.

M 3-1 (PN G242.6-11.6). Has general departures from axisymmetry and from mirror-symmetry

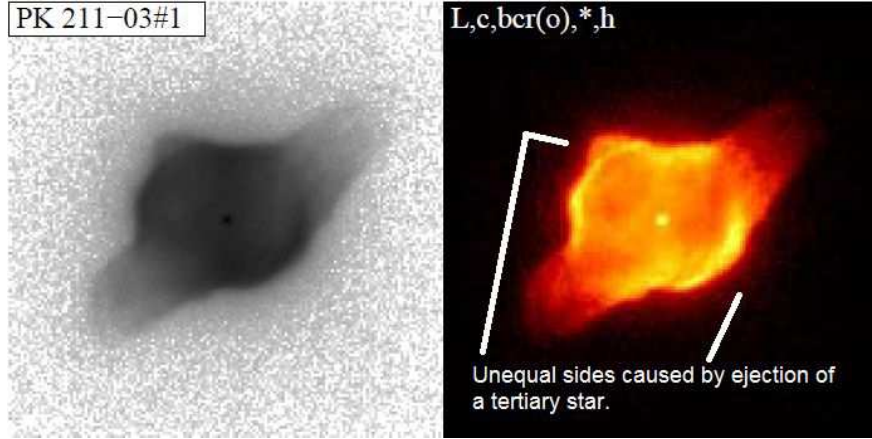


Fig. 2.— An image of M 1-6 from Sahai et al. (2011). I suggest that the departure from both mirror-symmetry and from axisymmetry might have been caused by the ejection of the tertiary star from the tight binary system. Despite these deviations, this PN is not as ‘messy’ as expected when the tight binary stars merge.

as those in M 1-6 (Schwarz et al. 1992).

3.3. Drowning star

3.3.1. Evolution

In this evolutionary route the triple-stellar system starts more or less as in the stellar ejection one, and the tight binary system breaks-up as a result of dynamical instability. However, the dynamical instability results in one star moving toward the giant envelope, instead of to the opposite direction, and with a low specific angular momentum. The dynamical interaction ‘drowns’ one of the stars of the tight binary system in the AGB envelope. This can happen before the tight binary system touches the envelope, or after.

We now have a triple-stellar system composed of a CEE of the AGB star and the drowning star of the tight binary system, with a third star orbiting at a distance of $a_{\text{out}} \approx 1$ AU. There are four types of possible outcomes, depending mainly on the relative masses of the three stars. (1) If the two stars of the tight binary system are relatively massive, then the drowning star manages to eject the AGB envelope. The outcome is a triple-stellar system of a star orbiting the core-remnant at $a_{\text{in}} \approx 1 - 10 R_{\odot}$, and the other one orbiting the central binary system at $a_{\text{out}} \approx 1$ AU. (2) If the drowning star is not massive enough to eject the AGB envelope, it merges with the AGB core. The other star can then survive, either with no more interaction with the AGB envelope, or experience a

GEE phase. The surviving star ends at a large orbital separation of $\approx 1 - 3$ AU, depending on how much mass was ejected from the AGB star during the merger process of the core with the drowning star. (3) The drowning star does not eject enough AGB envelope mass, and the other star enters a CEE phase. This star survives and ends like in a regular binary interaction. (4) The drowning star does not eject enough AGB envelope mass, and the other star enters a CEE phase. This star is not massive enough, and it merges with the core. The outcome is a single star system.

3.3.2. *The descendant PNe*

The main difference in the morphologies of the descendant PNe in the present evolutionary route to those described in sections 3.2 and 3.4, is that no large, or not at all, departure from axisymmetry, or more generally no departure from point-symmetry, is expected. Crudely, the evolution can be describes as composed of three intensive mass loss episodes. (i) The tight binary system accretes mass from the AGB envelope via a Roche lobe overflow. It is expected to launch jets and form a bipolar structure. (ii) A CEE of the drowning star inside the AGB envelope. Mass loss with concentration toward the equatorial plane might take place. (iii) A CEE, or a GEE, or a Roche lobe overflow interaction of the other star with the AGB star takes place. Another bipolar structure and/or another equatorial mass loss event are expected. If the initial plane of the tight binary system and the triple-stellar system are not parallel to each other, the two pairs of lobes and/or the two equatorial mass ejections will not be parallel to each other. A large scale point-symmetric PN is expected.

The following PNe have morphologies that might be compatible with the expectation of this evolution.

IPHAS PN-1 This PN contains two pairs of lobes, one inside the other, and highly inclined to each other (Mampaso et al. 2006). There is no large scale departure from point-symmetry

PN G358.9+03.4 (Sahai et al. 2011). This PN contains two pairs of lobes highly inclined to each other, and one pair is larger than the other. As evident from Fig. 3 no large departure from point-symmetry is observed.

Frosty Leo (IRAS 09371+1212) (Castro-Carrizo et al. 2005). This is a proto-PN, that like PN G358.9+03.4 contains two pairs of lobes highly inclined to each other, and one pair is larger than the other. The small pair of lobes is actually a complicated structure, where more small lobes are observed. This complicated structure might come from a triple-stellar evolution.

NGC 6302 (PN G349.5+01.0) (e.g., Meaburn et al. 2005; Szyszka et al. 2011). It has a well define bipolar structure, but with another pair of lobes protruding from the main bipolar structure. The axis of the protruding pair is inclined to that of the bipolar nebula, and the two lobes of the protruding pairs are not of equal size. Soker & Kashi (2012) proposed that the bipolar structure of

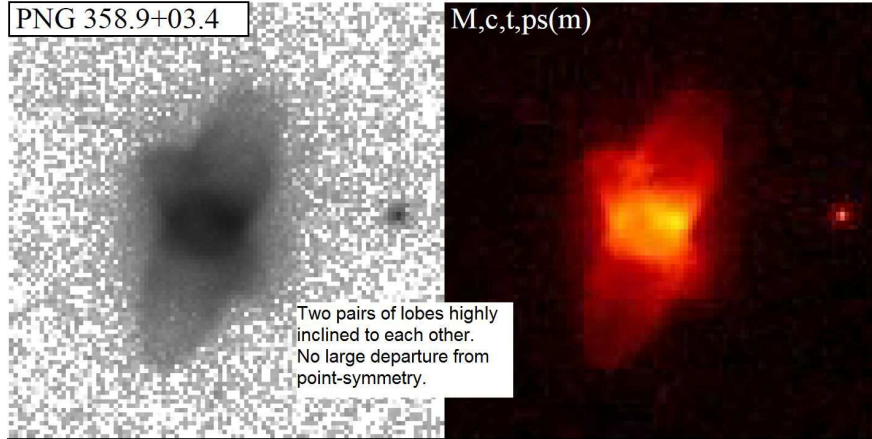


Fig. 3.— An image of PN G358.9+03.4 from Sahai et al. (2011). It presents a PN with two pairs of lobes highly inclined to each other and no large scale departure from point-symmetry. It might be compatible with the evolutionary route of a drowning star.

NGC 6302 was formed in an ILOT event.

3.4. Tight binary merger

3.4.1. Evolution

In this case the two stars enter a CEE or a GEE phase. The gravitational drag on the two stars of the tight binary system is more influential than the three-body dynamical instability, and the two stars merge. Accretion of mass by one or two of the tight binary stars also decreases the orbital separation. Most likely they merge well inside the envelope. As evident from equation (7), the energy released in the merger process is large. A large fraction of one side of the envelope can be ejected at high velocities, and a binary system survives: the primary and the secondary with the mass it accreted from the destroyed tertiary star (only a fraction of the destroyed tertiary star is accreted by the secondary star).

Let us consider one example from the large parameter space. Say a secondary of mass and radius of $M_2 = 0.5M_\odot$ and $R_2 = 0.5R_\odot$, respectively, accretes $M_{\text{acc}} = 0.1M_\odot$ of the destroyed tertiary star. By equation (4) the released energy is $E_{\text{m},23} \approx 2 \times 10^{47}$ erg. The accretion process lasts for about the viscosity time of the accretion disk. By equation (2) from Kashi & Soker (2015) the viscosity time is about two weeks. If this energy is channelled to eject, say, $M_{\text{env-ej}} = 0.5M_\odot$ of the envelope mass, the initial velocity of the ejected envelope mass is $v_{\text{env-ej}} \approx 200 \text{ km s}^{-1}$. This is the escape speed from $\approx 10R_\odot$ from the core. So if the merger occurs at a radius of

$\gtrsim 20R_{\odot}$, the ejected envelope chunk is ejected at a relatively high speed.

The fast ejected envelope mass can collide with previously ejected mass, and kinetic energy is channelled to thermal energy and radiation. An energy of $\approx 10^{47}$ erg can be radiated in several weeks. These are close to the radiated energy and time scale of the ILOT of the AGB star NGC 300 OT2008-1 (NGC 300OT; Monard 2008; Bond et al. 2009; Berger et al. 2009). So one of the outcome of this merger of the tight binary system can be an ILOT event in an AGB star.

The large released energy facilitates the envelope removal, and the final orbital separation of the binary system, the core and secondary star, can be relatively large. As a large mass of the envelope is ejected with high momentum to one side, the surviving binary system composed of the giant and the secondary star moves to the other. In the example above, let us take the terminal velocity of the one-sided ejected mass $M_{\text{env-ej}} = 0.5M_{\odot}$ to be 100 km s^{-1} . Let the rest of the primary mass be $3.5M_{\odot}$, which together with the secondary is $4M_{\odot}$. Although the surviving system is eight times as massive as the ejected mass, its velocity relative to the center of mass is lower than $100/8 = 12.5 \text{ km s}^{-1}$. This is because the ejected envelope mass is not a point mass, but rather it spreads over a large solid angle. Overall, the surviving binary system might move at $\approx 5 - 10 \text{ km s}^{-1}$ relative to the center of mass. The ejection of a large envelope fraction to one side, and the motion of the surviving system, that continues to lose mass, to the other side results in a ‘messy’ (irregular) PN.

3.4.2. *The descendant PNe*

The descendant nebula has no axisymmetry, and in some cases not even a mirror symmetry about the orbital plane. A binary system survives, but it is displaced from the nebular center, if a center can be defined at all for the expected ‘messy’ PN. It is expected to have one side much brighter than the other. The bright massive side can be larger or smaller than the faint size, depending on later evolution, e.g., acceleration by a fast wind.

The following PNe have morphologies that are compatible with the expectation of a tight binary system merger inside the progenitor envelope.

Sh2-71 (PN G035.9-01). This bipolar PN is not really a ‘messy’ PN, but it lacks a well define symmetry axis or a symmetry plane (Močnik et al. 2015). It is compatible with the expectation from the scenario discussed here when the energy released in the tight binary merger is not large.

Abell 46 (PN G055.4+16.0). In this PN the mass distribution departs from any symmetry. The companion to the central star has a mass of $0.15M_{\odot}$ (Corradi et al. 2015).

NGC 6210 (PN G043.1+37.7). This was mention by Soker (2004) as descendant of a triple-stellar system with tight binary being at a wide orbit (section 3.1.2 above). As evident from Fig. 4, this is

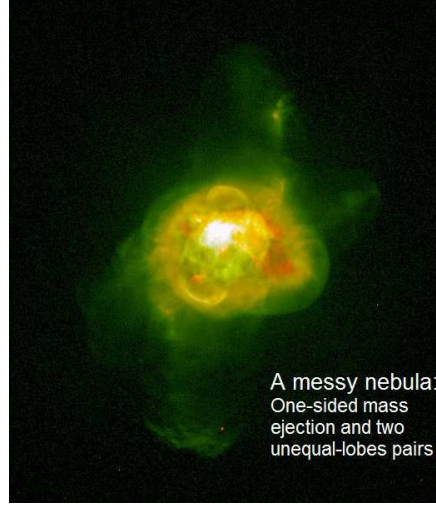


Fig. 4.— An image of NGC 6210 (from HST site), presenting a ‘messy’ PN that is compatible with the expectation from a tight binary system that launched jets and merged. Jet launching can occur after the merger process as well.

indeed a ‘messy’ PN (Balick 1987; Pottasch et al. 2009), and its morphology is better compatible with the expectation from a tight binary merger. The two unequal-lobes pairs might hint that the tight binary system launched jets before it merged.

He 2-11 (PN G259.1+00.9). It posses a departure from axisymmetry and mirror symmetry, although these deviations are not large, and its central star is a binary system with a K-type main sequence companion in a 0.609 d orbital period (Jones et al. 2014). The departure from pure axisymmetry and mirror symmetry might be compatible with a process of tight binary merger with a low mass M-type tertiary star or with a brown dwarf.

He 2-459 (PN G068.3-02.7). It has no lobes. One can define a symmetry plane, where the mass in one side is more extended, and in the other side there is a dense arc (Sahai et al. 2011). It is presented in Fig. 5.

He 2-71 (PN G296.4-06.9) (Sahai & Trauger 1998); **He 2-105 (PN G308.6-12.2)** (Schwarz et al. 1992); **He 2-113 (PN G321.0+03.9)** (Sahai et al. 2000, 2011). These are other PNe that lack both pure axisymmetry and mirror symmetry, although they have one or more pairs of lobes; some cases the two lobes are not equal.

4. SUMMARY

I conducted a preliminary study of the possible outcomes from the strong interaction of PN progenitors with a close tight binary system. I estimated that about one out of eight PNe that

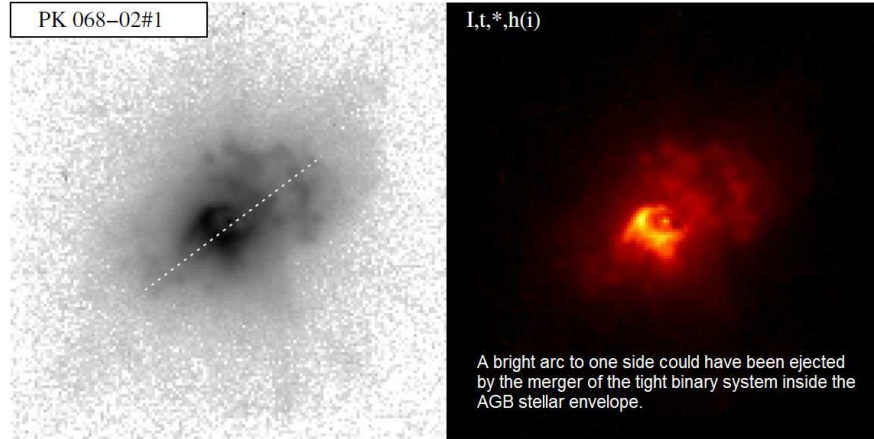


Fig. 5.— An image of Hen 2-459 from Sahai et al. (2011). The pronounced dipole morphology is compatible with the expectation of mass ejected in a merger process of the tight binary system inside the AGB envelope.

evolved through binary interaction, actually experienced triple-stellar evolution, including brown dwarfs tertiary stars (eqs. 1 and 2). Two types of energy can be associated with the tight binary system, the energy that is required to break it up (eq. 3), and the gravitational energy that is released if the two stars of the tight binary system merge (eq. 4). These are not negligible relative to the binding energy of the envelope. In particular, the energy released by the merger process can be large and leads to ejection of a large portion of the envelope in one direction and possibly with high velocities. If part of the kinetic energy is channelled to radiation, an ILOT event of an AGB star might take place.

I also speculated on the possible morphologies of the descendant PNe of triple-stellar evolution. One should be aware that at this stage the affiliation of specific PN morphologies to the different triple-stellar evolutionary routes is highly uncertain, and is qualitative and objective. As well, many features, like departure from axisymmetry, might be caused also by a binary interaction with no need for a triple-stellar system. However, binary interactions are not expected to lead to a very large departures from axisymmetry, and are not expected to cause any departure from mirror symmetry.

I concentrated on four evolutionary routes. The first one is of a tight binary system that never enters a CEE or a GEE phase, and survives to the PN phase (section 3.1). To form a bright PN either the tight binary system must be close to the AGB star, or a fourth star closer to the AGB star is required. In the first case a Roche love over flow is likely to take place, resulting in massive jets launched by the tight binary system, that form bipolar PN. In the second case the fourth star interacts strongly with the AGB star. Evolutionary routes with a quadruple-stellar system are

rare, and it is hard to picture the expected morphology of the descendant PNe of such systems. I speculated, non the less, on something like the morphology of NGC 6578 that is presented in Fig. 1.

In the second evolutionary route the tight-binary system breaks-up as a result of the gravity of the primary star (section 3.2). This occurs when the tight binary system comes closer to the AGB star as a result of tidal forces, and a GEE takes place. One star of the tight binary system, more likely the tertiary star, is ejected from the system or is thrown to a large and eccentric bound orbit. This causes the binary system that is left, of the AGB star and the secondary star, to move in the other direction. This leads to departure from axisymmetry of the descendant PN. If the two orbital planes, of the tight binary system and of the triple-stellar system, are not parallel to each other, the PN will posses no mirror symmetry either. One of the possible expected morphologies might be the one of M 1-6 as presented in Fig. 2.

In the third evolutionary route the dynamical instability breaks-up the tight binary system, and throws one star into the AGB envelope with low specific angular momentum; this star ‘drowns’ in the AGB envelope (section 3.3). The evolution can end up with one of four types of stellar systems. The descendant PN is expected to have an axisymmetry if the initial equatorial plane of the tight binary system is parallel to that of the triple-stellar system, and to posses point-symmetry if the planes are inclined to each other. No large scale departure from axisymmetry is expected. I speculated that one possible PN morphology is like that shown in Fig. 3.

In the fourth evolutionary route (section 3.4) the tight binary system merges inside the AGB envelope. The large amount of released gravitational energy can eject a large envelope mass in one direction. Both before and after merging, and definitely during the merging process, the system can launch jets. The PN has no axisymmetry and no point symmetry. If the two orbital planes are inclined to each other, the PN will neither posses mirror symmetry. The outcome is a binary system with a ‘messy’ PN. Possible PN morphologies are like those shown in Figs. 4 and 5.

In short, the main claim of this paper is that *‘messy’ PNe owe their structure to triple (or quadruple) stellar system interaction.*

I did not discuss in details cases where the tight binary system survived the GEE and/or the GEE phases, a scenario proposed by Bond et al. (2002) and Exter et al. (2010). In general the morphologies are expected to be similar to some of the cases of the drowning stellar scenario (section 3.3). If, for example, the two orbital planes are parallel, then the outcome can be as in binary evolution, but more extreme, e.g., an extreme ring as suggested by Bond et al. (2002) and Exter et al. (2010). If the two planes are inclined, a point symmetric PNe might be formed, with a pair of lobes inclined at an angle different than 90° to a dense equatorial ring or torus. Namely, the descendant PNe of surviving tight binary systems are expected to posses axial-symmetry or

point-symmetry despite the large departure from spherical-symmetry. They will not be ‘messy’.

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